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RESEARCH MEMORANDUM

STATISTICAL MEASUREMENTS OF LANDING CONTACT CONDITIONS

OF FIVE MILITARY AIRPLANES DURING

ROUTINE DAYTIME OPERATIONS

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STATISTICAL MEASUREMENTS OF LANDING CONTACT CONDITIONS OF FIVE MILITARY AIRPLANES DURING ROUTINE DAYTIME OPERATIONS

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SUMMARY

Statistical measurements of landing contact conditions have been obtained, by means of a special photographic technique, of about 100 to 300 landings for each of five types of military airplanes made during routine daytime operations in clear air at Langley Air Force Base, Langley Field, Va. The airplane types were the jet-propelled Republic F-84F, Lockheed F-94C, Martin B-57, Lockheed T-33, and the propeller-driven Douglas B-26. From the measurements, vertical velocities, bank angles, rolling velocities, and airspeeds at the instant before contact, and touchdown locations from the start of the 8,000-foot runway have been evaluated; and a limited statistical analysis of the results has been made.

The analysis indicates that out of 1,000 landings the range of values of contact conditions likely to be equaled or exceeded once for the five airplanes investigated were as follows: (1) vertical velocity, 4 to 5 ft/sec, with the exception of the data for the Republic F-84F airplane which indicated a value of vertical velocity about double that for the other types; (2) bank angle, $3\frac{1}{2}^{\circ}$ to 7°; (3) rolling angular velocity toward the first wheel to touch, 6 to 12 deg/sec, and away from first wheel, 5 to 10 deg/sec; (4) airspeed at contact, 142 knots to 184 knots; (5) distance of touchdown location from the start of the 8,000-foot runway, about 2,500 to 2,700 feet for all except the T-33, for which the value was 3,200 feet.

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INTRODUCTION

In order to aid in the development of more rational landing-loads design requirements and procedures, the National Advisory Committee for Aeronautics has been engaged in a project to obtain statistical measurements of landing contact conditions for various types of airplanes during routine operations. Results for 478 landings of present-day transport airplanes are reported in reference 1. Results for landing contact conditions of a heavy bomber and for the Boeing B-47 jet bomber are presented, respectively, in references 2 and 3.

As a continuation of the project to obtain similar information for other types of airplanes, particularly those types for which little data exist such as present-day and land-based small and medium jet aircraft, records have been obtained for a total of about 1,000 landings for the following aircraft types (approximate number of landings for each type given in brackets): (1) Lockheed F-94C jet interceptor [194], (2) Republic F-84F jet fighter bomber [300], (3) Lockheed T-33 jet trainer [166], (4) Martin B-57 jet bomber [109], and (5) Douglas B-26 twin-propeller bomber [224]. Vertical velocities, horizontal velocities, bank angles, rolling angular velocities at the instant before contact, and locations of touchdown points from the start of an 8,000-foot runway have been evaluated from the records. A limited statistical analysis of the results has been made and is presented herein.

APPARATUS AND METHOD

The measurements were made from 35-millimeter photographic records of the landings obtained according to a method described in reference 4. The equipment consists essentially of a constant-speed 35-millimeter motion-picture camera fitted with a telephoto lens of 40-inch focal length supported on a vertical shaft which provides for tracking the airplane only in azimuth. The 40-inch focal length lens permits setting up the camera at about 1,000 feet from the runway so that it offers no obstruction to aircraft on the airport proper. Further details of the method used to obtain the data and details of the reduction of the data with formulas used to obtain the landing contact conditions of sinking speed, horizontal speed, bank angle, and rolling velocity can be obtained from references 1 and 4. Location of touchdown points was determined from measured azimuth angles and simple triangulation. Photographs were made of about 1,200 airplane landings of which about 1,000 were suitable for evaluation and analysis. All landings photographed were made in the same direction on one runway which was 8,000 feet long. General specifications data for the airplanes photographed are given in table I.

PRECISION OF MEASUREMENTS

The precision of measurements in terms of probable error in the quantities determined as a result of errors in film reading and the error introduced by neglecting the vertical accelerations is as follows:

Vertical velocity, ft/sec	±0.1
Rolling velocity, deg/sec	±0.3
Bank angle, deg	±0.1
Horizontal velocity, ft/sec	±1.5
Location of touchdown point, ft	±5

For a more detailed account of sources of error and accuracy of the results, especially with regard to vertical velocity, see reference 4.

PRESENTATION OF RESULTS

The results are presented as probability curves in figures 1 to 5, respectively, for the following quantities: vertical velocity, bank angle, rolling angular velocity (both toward and away from the first wheel to touch), airspeed at contact, and location of touchdown point, for the five airplane types. The data points shown on the probability curves represent cumulative frequencies of the various quantities for the following class intervals: 0.5 ft/sec for vertical velocity, 0.5° for bank angle, 0.5 deg/sec for rolling velocity, 5 knots for airspeed at contact, and 400 feet for distance of touchdown point from the start of the runway. Probability data were arbitrarily faired by the Pearson type III probability curves determined in the manner described in reference 5. Values of the statistical parameters (mean value, standard deviation σ, and coefficient of skewness α_3) which were used in fitting the Pearson type III curves to the various distributions are listed in table II. The Pearson type III probability curves, which appear to fit the data reasonably well, provide a systematic fairing of the data, and permit some extrapolation to give an indication of the magnitude of the various quantities likely to be equaled or exceeded in a greater number of landings than were actually observed. The airspeeds at contact were determined as the sum of the measured horizontal speed and the parallel component (in the direction of the runway) of wind velocity measured at the control tower. The wind varied from calm up to a maximum of about 17 knots during the tests, with attendant cross-wind components perpendicular to the runway up to a maximum of 13 knots and with a maximum variation in wind components parallel to the runway from a 15-knot headwind to a 7-knot tailwind. Calm conditions, or headwinds up to 10 knots existed for 76 percent of the landings; 11- to 15-knot headwinds were present for 18 percent of landings. The remaining 6 percent of the landings were made in tailwinds, with 5 percent at velocities of 1 to 2 knots, and 1 percent at about 7 knots. The effect of the gusty-wind conditions, a factor which was found to have a significant effect on sinking speed, bank angle, and rolling velocity for the 478 transport airplane landings reported in reference 1, could not be determined in the present analysis inasmuch as the gusty-wind condition (defined in ref. 1) was nonexistent during the present tests.

Data for individual landings are not included in this report but can be made available upon request.

DISCUSSION

Vertical Velocity

The probability distributions of vertical velocity for four of the five types of airplane shown in figure 1 indicate that the distributions are essentially similar with no vertical velocity exceeding a value of 5 ft/sec. As indicated in table II, the mean values of vertical velocity for these four types are all around 1.00 ft/sec and the standard deviations are about 0.65 ft/sec. The Pearson type III probability curves shown in figure 1 indicate that for each of these four airplane types 1 out of 1,000 landings might be expected to equal or exceed 4 to 5 ft/sec.

The probability distribution of vertical velocities for the F-84F airplane appears to be quite different from the other four in a number of aspects. A comparison of the results for this type with those for the other four indicates a substantially greater probability for exceeding a given vertical velocity. For example, roughly 1 out of 10 Republic F-84F landings exceeded 3 ft/sec as compared with 1 out of about 75 landings for the other four airplanes. The mean value of vertical velocity (1.72 ft/sec) and the standard deviation (1.22 ft/sec) for the F-84F airplane (see table II) are larger by about 70 percent, and 100 percent, respectively, than the values of those quantities for the other four airplanes. Thus, it appeared that the value of vertical velocity likely to be equaled or exceeded once out of 1,000 landings of the F-84F airplane would be about double that for the other airplanes.

In addition to the general higher level of vertical velocities, the distribution for the F-84F airplane shown in figure 1 indicates a rather irregular form, despite the larger number of observations (302). In fact, the Pearson type III probability curve did not appear to represent the data adequately and is, therefore, not shown. The curve was particularly inadequate at the higher vertical velocities and underestimated the probabilities of exceeding the four largest observed values, namely, 6.8 ft/sec, 7.2 ft/sec (two observations), and 10.8 ft/sec, which were substantially larger than the bulk of the data. These four landings were noted by the observer to have little or no flare prior to touchdown. The preceding results suggest that there may be a critical threshold in one of the approach conditions or in a combination of approach conditions (glide path, height of flare initiation, control manipulation, airspeed . . .) beyond which the vertical velocities at contact are much greater than would be expected normally. Thus, the possibility of a second frequency distribution for the landings which have exceeded the critical threshold is indicated. For the F-84F airplane, the average of the four vertical-velocity values showing the large deviation from the probability trend was about 8 ft/sec with a maximum of 10.8 ft/sec, as compared with the average of 1.64 ft/sec and a maximum of 4.6 ft/sec obtained for the remainder of the landings. In order to obtain a better defined probability curve in the range of higher values of vertical velocity for the F-84F airplane, it would be necessary to ascertain the frequency distribution of this second category of landings, which would probably require measurements of many times the number of landings observed in the present investigation.

Bank Angle

The curves for the probability of equaling or exceeding given values of bank angle (fig. 2) show that for 1 out of 1,000 landings the values of bank angle that will be equaled or exceeded range from about $3\frac{1}{2}^{\circ}$ for the B-57 and B-26 airplanes to about 7° for the F-84F and F-94C airplanes, with the T-33 at about 5°; thus, a substantial spread for the five types of airplanes is indicated. Frequency distributions of angle of bank indicate ratios of left bank to right bank of 3 to 1 for the T-33, B-26, and F-94C; $3\frac{1}{2}$ to 1 for the F-84F, and 9 to 1 for the B-57. The 4 to 1 ratio of left bank to right bank for the transports (ref. 1) was tentatively explained by reason of the 10 to 1 ratio of cross winds from the left, and the pilot's location on the left. However, the present disproportionately large number of left bank angles at contact cannot be similarly explained inasmuch as cross-wind components from the left and right were essentially equal (a ratio of about 10 to 9), and four of the five airplanes were either single place or a tandem arrangement. There is no readily apparent explanation for this difference in number of left and right bank angles; however, it is doubtful if the disproportion is of any real import.

Rolling Velocity

The probability curves for rolling velocity (fig. 3) indicate that, for the F-94C, F-84F, and B-26 airplanes, the probability of equaling or exceeding a given rolling velocity is greater for rolling toward the first wheel to contact than for rolling away from the first wheel to contact. The T-33 indicated essentially the same probability for both cases, and the B-57 indicated a greater probability for equaling or exceeding a given rolling velocity away from the first wheel to contact, up to about 4 deg/sec. For 1 out of 1,000 landings the rolling velocities toward the first wheel to contact likely to be equaled or exceeded ranged from about 6 deg/sec to 12 deg/sec for the five airplanes; for rolling away from the first wheel to contact, the values ranged from about 5 deg/sec to 10 deg/sec.

Airspeed at Contact

The probability curves for airspeed at contact for the five types of airplanes are plotted together (fig. 4) for convenience rather than for direct comparison, inasmuch as it is realized that a comparison of absolute airspeeds at contact for airplanes of widely different wing loadings and stalling speeds has little significance. The airspeed expressed in percent above the stalling speed, a quantity more suitable for comparative purposes, could not be determined because the weights of the aircraft at landing needed for the evaluation were not obtained. For 1 out of 1,000 landings the approximate airspeed at contact likely to be equaled or exceeded for the five airplanes investigated were as follows: T-33, 142 knots; B-26, 148 knots; B-57, 151 knots; F-94C, 165 knots; F-84F, 184 knots. The mean airspeeds (also in knots) for each of the airplanes in the same order as above were 113.8, 110.8, 117.4, 139.8, and 147.0. The maximum measured airspeed at contact, 184 knots, was for an emergency landing by an F-84F airplane. However, three other F-84F nonemergency landings ranged between 175 and 180 knots.

In order to obtain some idea of the percentage by which contact airspeeds exceeded the stalling speeds for these aircraft, figures for the nominal average landing weight of each airplane for the particular missions during the time the landings were being photographed were obtained from operations personnel. The mean airspeeds listed previously, combined with the airplane stalling speeds (in the landing condition) corresponding to the furnished nominal average landing weight (values listed in table I), yield average values of percentages by which contact airspeeds exceeded stalling speeds for the five airplanes as follows: B-26, 20 percent; T-33, 23 percent; B-57, 43 percent; F-94C, 13 percent; and for the F-84F, 25 percent. These values include a correction to account for the temperatures existing during the tests which were in all cases above standard.

Location of Touchdown Point

Frequency distributions of the percentage of landings occurring in successive 400-foot intervals from the start of the 8,000-foot runway indicated that the greatest percentage of landings occurred in the 400-foot interval between 800 and 1,200 feet for all five airplanes. Almost all airplanes were on the ground by the 2,400-foot point except for about 1 percent (6 landings of the T-33). The percentages of landings of each of the five airplanes which had touched down in the first 1,000 feet from the start of the runway were as follows: T-33, 54 percent; B-26, 56 percent; B-57, 57 percent; F-94C, 60 percent; and the F-84F, 68 percent. These percentages were taken from the actual data and not from the faired curves of figure 5.

The curves for the probability of touching down at or beyond given distances from the start of the 8,000-foot runway (fig. 5) indicate that for four of the five airplanes (the exception being the T-33) only 1 out of 1,000 touchdowns would be expected to occur at or beyond about 2,500 to 2,700 feet; for the T-33, 1 out of 1,000 would be expected to occur at or beyond the 3,200-foot point. It should be noted that at 1,000 feet from the start of this 8,000-foot runway, on which all airplane landings of the present investigation were made, there is a junction where taxiways intersect the runway on both sides. The fact that this junction is located at the center of the 400-foot interval in which, as noted above, the greatest percentage of landings occurred for all five airplanes indicates that the pilots may be using the junction as a landing target. These comments and data are offered for consideration in connection with the suggestion made by members of various agencies that a target be painted on runways 500 to 1,000 feet from the runway threshold as an aid to reducing nonemergency undershoot accidents. In the course of obtaining the present statistical data (about 1,000 usable landings) none of the approximately 1,300 landings observed touched short of the runway in the undershoot area.

CONCLUSIONS

Results of the analysis of about 1,000 landings obtained during routine daytime operations in clear air of five military airplanes landing on a runway 8,000 feet long have indicated the following conclusions:

(1) Out of 1,000 landings the values of vertical velocity likely to be equaled or exceeded once for four of the five airplanes varied from 4 to 5 ft/sec. The probability distribution of vertical velocity for the Republic F-84F airplane type appeared to have a general higher level as compared with the other four airplanes and indicated a rather irregular form, despite the larger number of observations. It appeared that

the value of vertical velocity likely to be equaled or exceeded once out of 1,000 landings of the F-84F airplane would be about double that for the other airplanes.

(2) For 1 out of 1,000 landings the values of bank angles likely to be equaled or exceeded ranged from about $3\frac{1}{2}^{\circ}$ to 7° for the five airplanes.

(3) In general, the probability of equaling or exceeding a given rolling angular velocity was greater for rolling toward the first wheel to touch; for 1 out of 1,000 landings, the rolling angular velocities toward the first wheel to contact likely to be equaled or exceeded ranged from 6 deg/sec to 12 deg/sec; for rolling away from the first wheel the values ranged from 5 deg/sec to 10 deg/sec.

(4) Out of 1,000 landings, the airspeed at contact likely to be equaled or exceeded once for the five airplanes was 142 knots for the Lockheed T-33, 148 knots for the Douglas B-26, 151 knots for the Martin B-57, 165 knots for the Lockheed F-94C, and 184 knots for the Republic F-84F.

(5) In 1 out of 1,000 landings four of these airplanes would be expected to touch down at or beyond about 2,500 to 2,700 feet.

The T-33 would be expected to touch down at or beyond the 3,200-foot point once out of 1,000 landings.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 4, 1956.

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5. Kenney, John F.: Mathematics of Statistics. Pt. II. D. Van Nostrand Co., Inc., 1939, pp. 45-51.

TABLE I

GENERAL SPECIFICATION DATA

Airplane	Maximum gross weight, lb	Wing area, sq ft	Maximum wing loading, lb/sq ft	Main axle wheel tread, ft	Nominal average landing weight, lb	Stalling speed,[1] knots	Maximum lift coefficient, landing condition
B-26	32,400	540	60	19.5	29,000	90	1.96
T-33	15,000	238	63	8.8	11,000	90	1.72
B-57	53,400	960	56	15.8	34,000	80	1.63
F-94C	19,200	238	81	9.2	17,000	120	1.45
F-84F	27,000	325	83	20.4	16,000	114	1.12

[1]For nominal average landing weight, gear and flaps down, 0° bank, standard conditions.

TABLE II

VALUES OF STATISTICAL PARAMETERS FOR LANDING-CONTACT CONDITIONS

(a) Vertical velocity

Airplane	Number of landings	Maximum vertical velocity, ft/sec	Mean vertical velocity, ft/sec	Standard deviation, σ, ft/sec	Coefficient of skewness, α_3
B-26	224	3.9	1.31	0.67	0.77
T-33	166	4.6	1.03	0.68	1.75
B-57	109	3.1	0.95	0.63	1.20
F-94C	194	4.6	1.01	0.67	1.48
F-84F	302	10.8	1.72	1.22	2.46

(b) Bank angle

Airplane	Number of landings	Maximum bank angle, deg	Mean bank angle, deg	Standard deviation, σ, deg	Coefficient of skewness, α_3
B-26	224	3.1	1.07	0.71	0.52
T-33	166	4.2	1.20	0.86	1.02
B-57	109	2.8	1.09	0.62	0.31
F-94C	194	5.4	1.66	1.21	0.98
F-84F	298	5.9	1.41	1.12	1.16

(c) Rolling velocity

Airplane	Number of landings		Maximum rolling velocity, deg/sec		Mean rolling velocity, deg/sec		Standard deviation, σ, deg/sec		Coefficient of skewness, α_3	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
B-26	122	102	4.8	4.5	1.25	1.01	1.08	0.91	1.32	1.48
T-33	86	80	9.5	7.8	2.47	2.29	1.73	1.88	1.14	0.96
B-57	44	65	4.6	4.4	1.36	1.28	1.15	1.14	1.31	0.85
F-94C	112	82	7.7	4.6	2.47	1.58	1.86	1.21	0.79	0.66
F-84F	174	124	11.4	7.6	2.43	1.72	2.05	1.44	1.40	1.23

(d) Airspeed

Airplane	Number of landings	Maximum airspeed, knots	Mean airspeed, knots	Standard deviation, σ, knots	Coefficient of skewness, α_3
B-26	224	147	110.8	8.65	0.88
T-33	166	133	113.8	6.25	0.96
B-57	109	139	117.4	9.70	0.21
F-94C	194	160	139.8	8.55	-0.08
F-84F	299	184	147.0	10.80	0.20

(e) Distance from start of runway

Airplane	Number of landings	Maximum distance, ft	Mean distance, ft	Standard deviation σ, ft	Coefficient of skewness, α_3
B-26	224	2,100-2,200	986	460	0.39
T-33	166	2,300-2,400	1,071	521	0.69
B-57	111	2,200-2,300	978	432	0.58
F-94C	198	2,200-2,300	964	394	0.56
F-84F	302	2,200-2,300	858	426	0.56

(a) Rolling toward first wheel to contact.
(b) Rolling away from first wheel to contact.

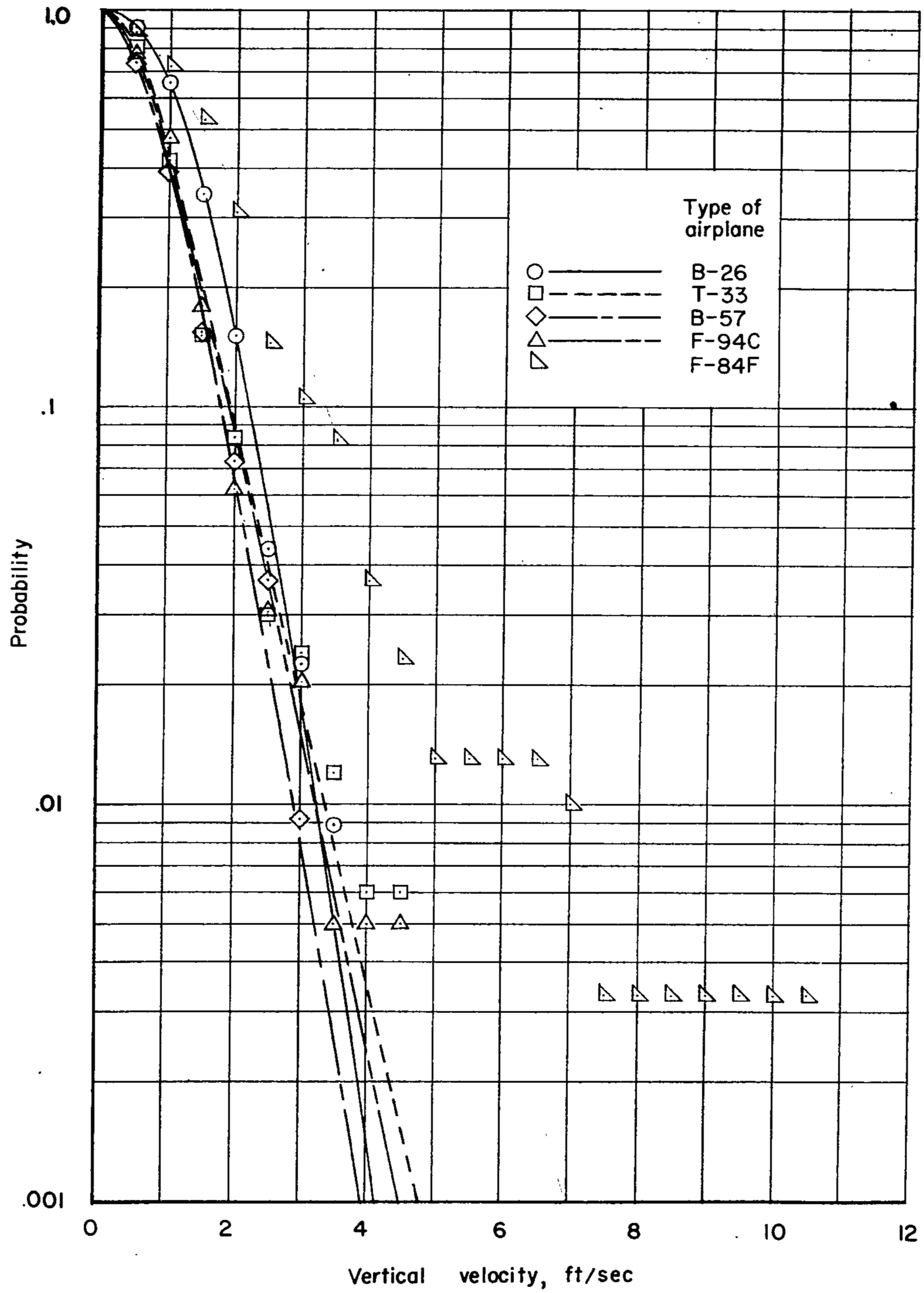


Figure 1.- Probability of equaling or exceeding vertical velocity for five types of airplanes.

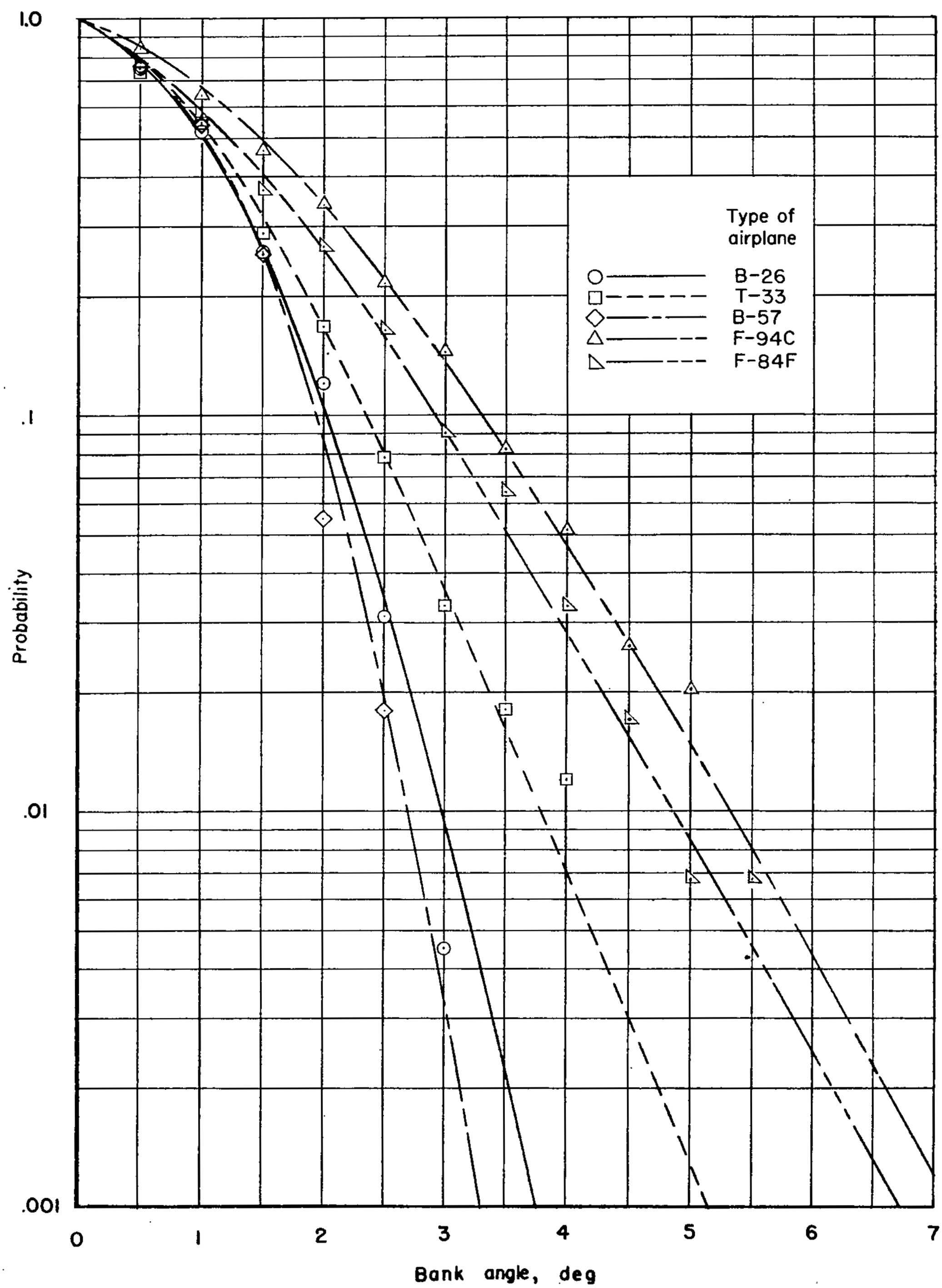
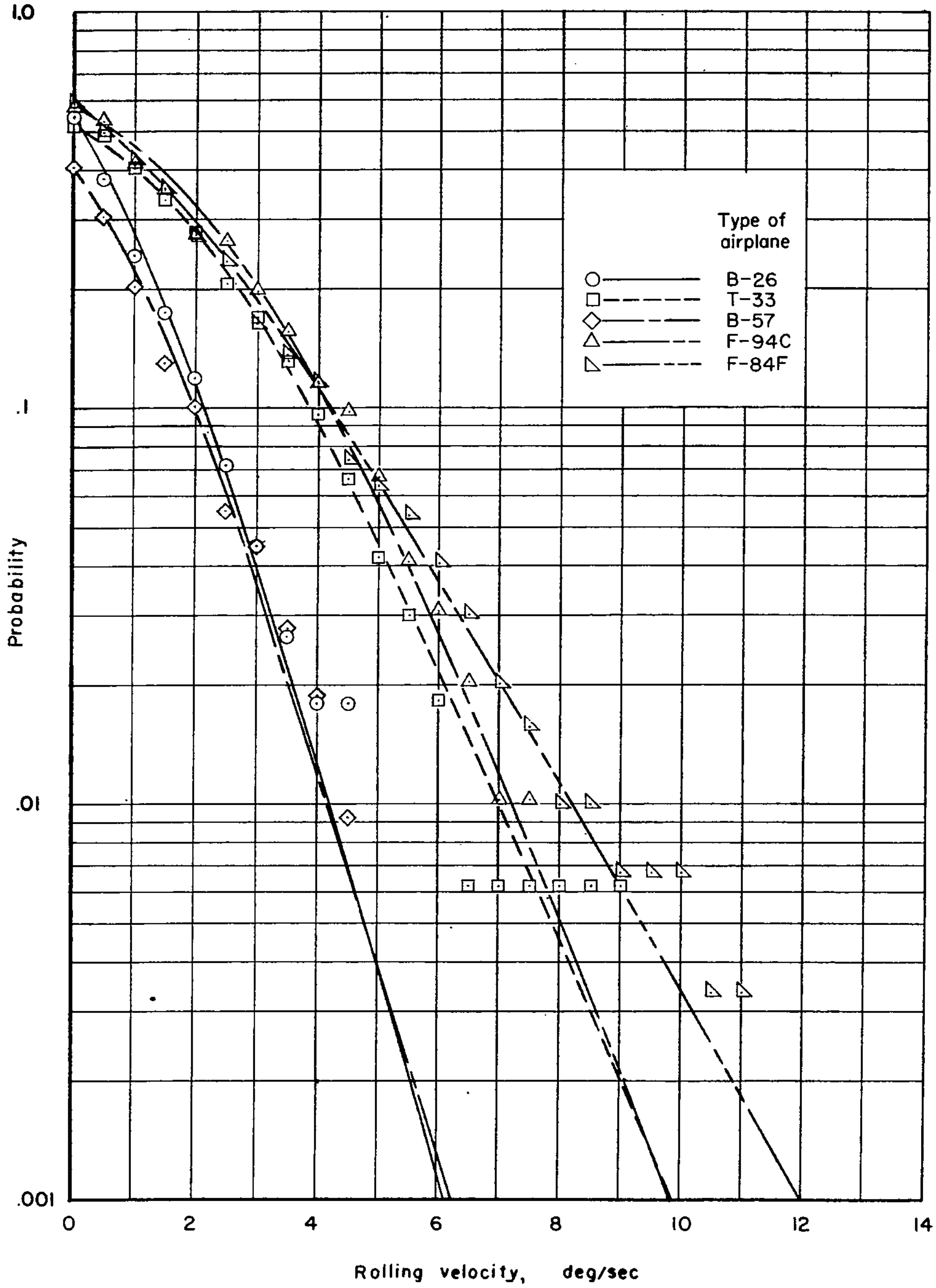
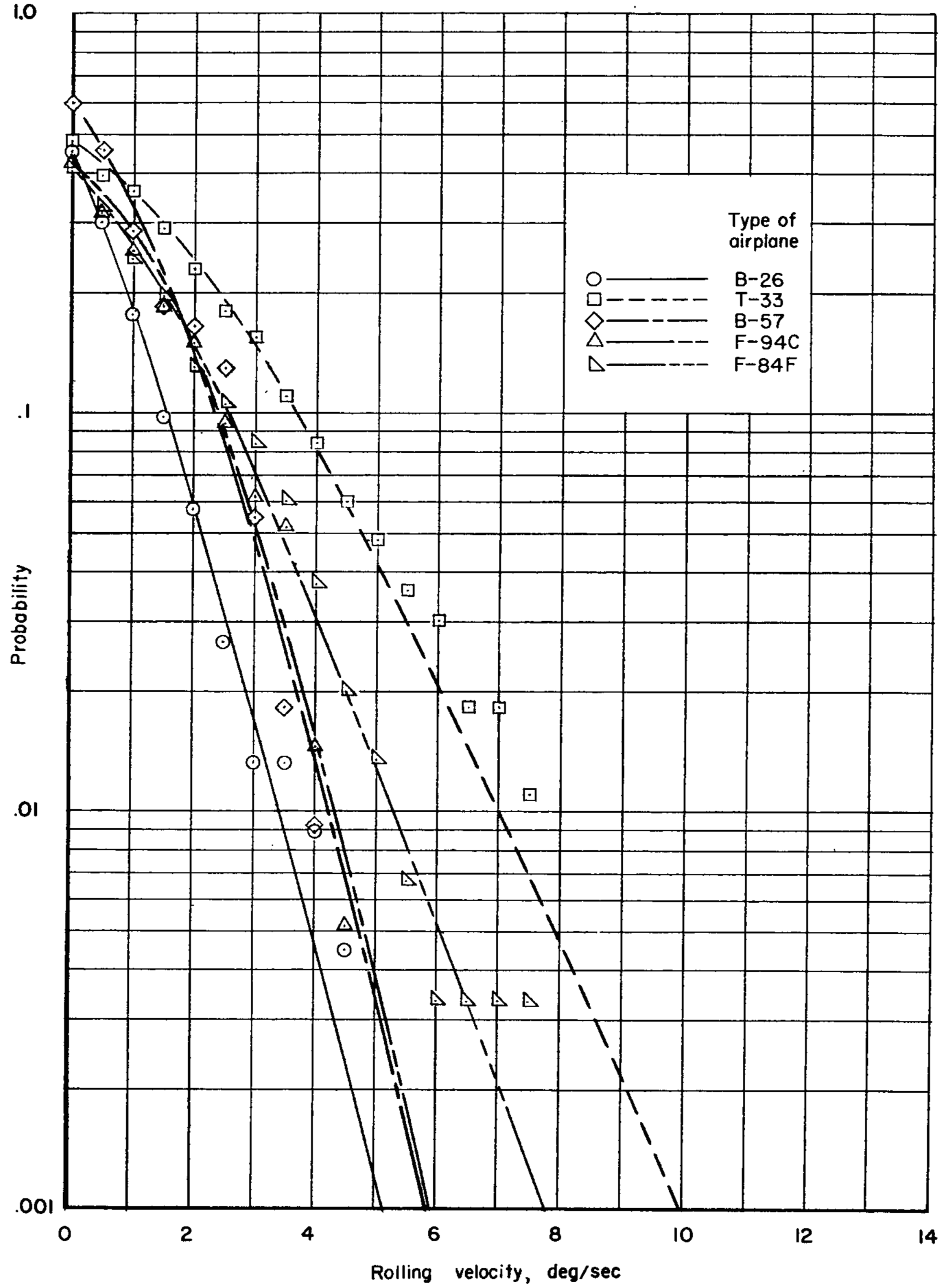


Figure 2.- Probability of equaling or exceeding bank angle for five types of airplanes.



(a) Toward first wheel to contact.

Figure 3.- Probability of equaling or exceeding rolling velocity toward and away from the first wheel to touch for five types of airplanes.



(b) Away from first wheel to contact.

Figure 3.- Concluded.

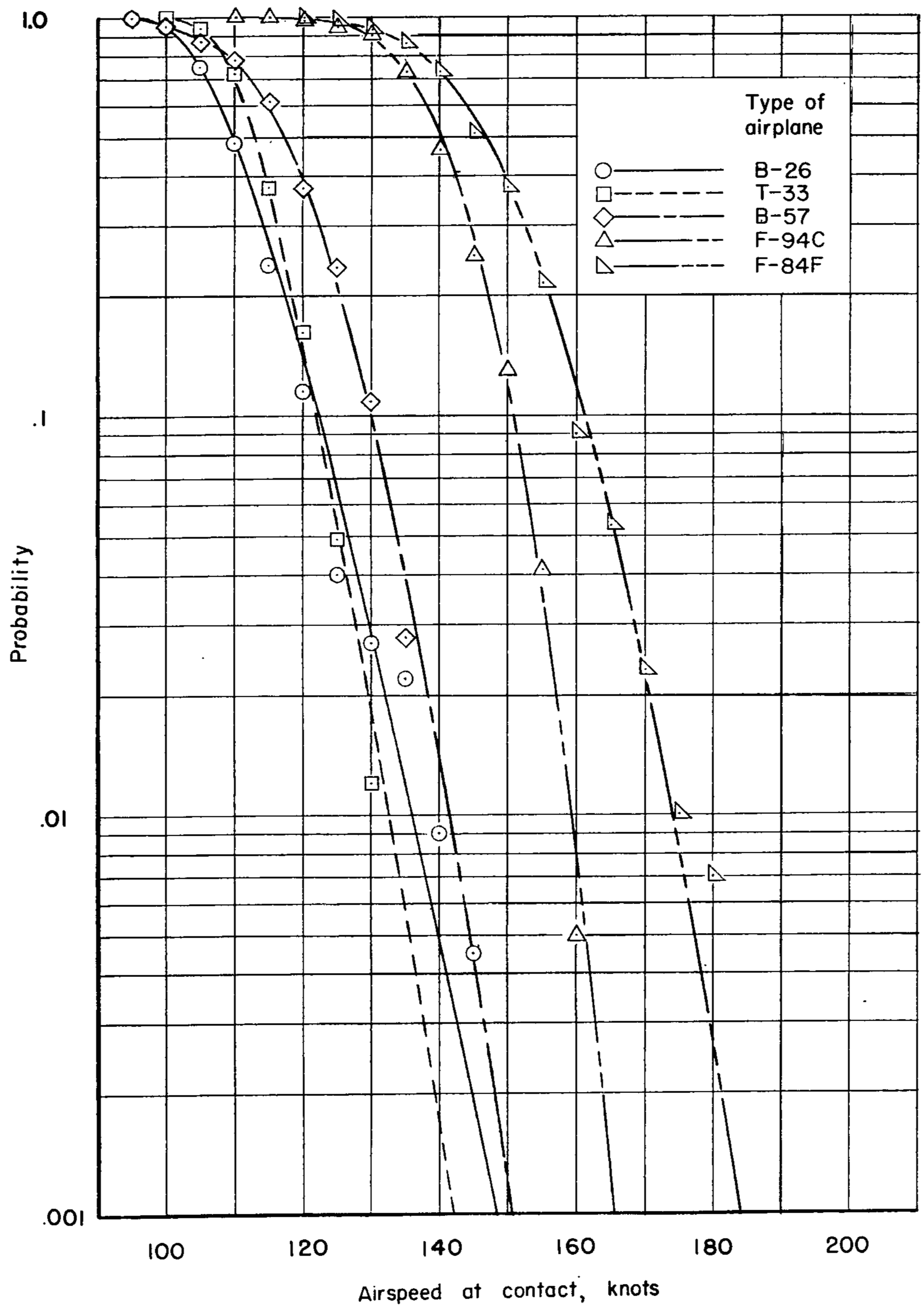


Figure 4.- Probability of equaling or exceeding various airspeeds at contact for five types of airplanes.

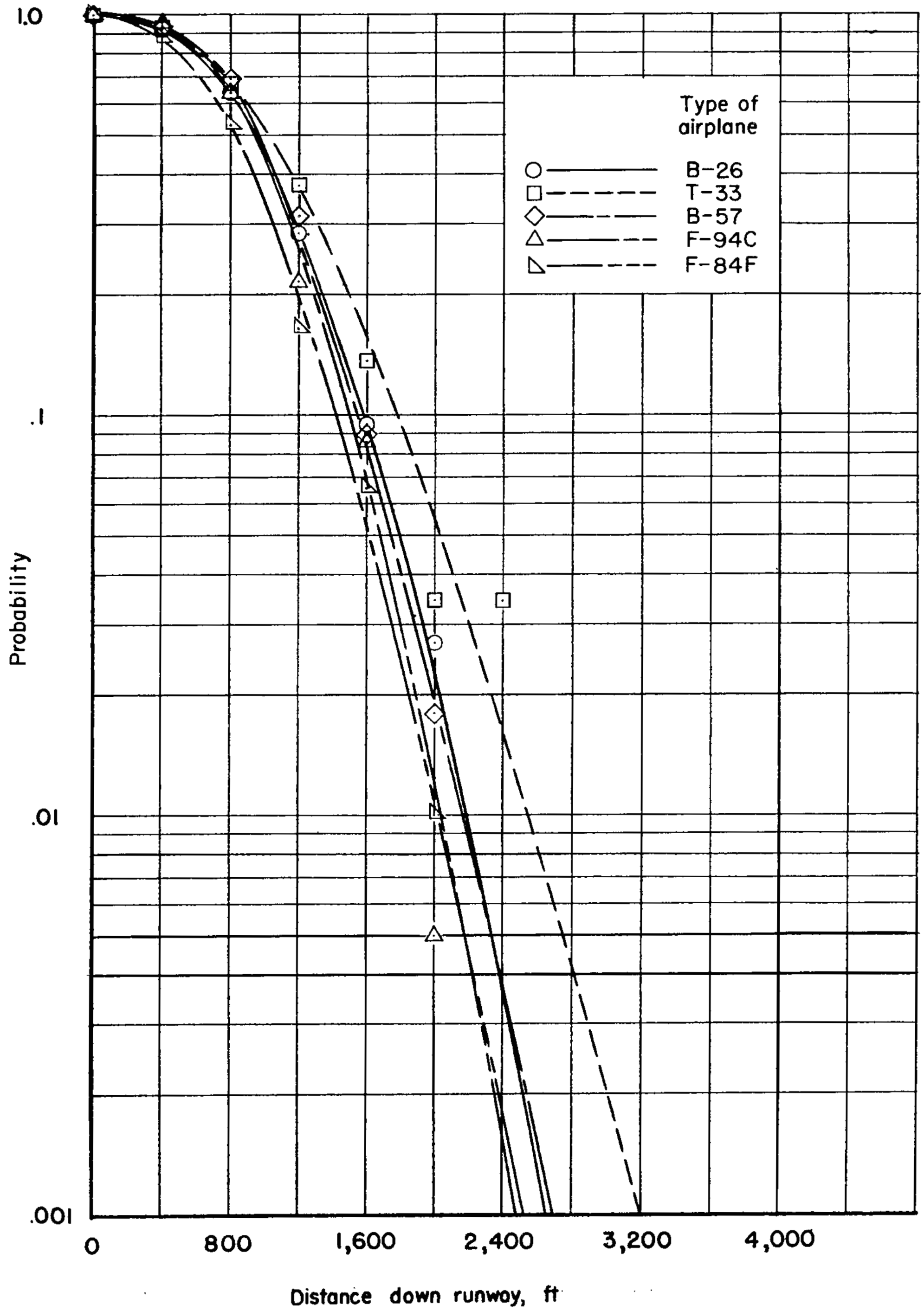


Figure 5.- Probability of touching down at or beyond given distances from the start of a runway 8,000 feet long for five types of airplanes.

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